EARTH SCIENCES
RESEARCH JOURNAL
Earth Sci. Res. J. Vol. 27, No. 3 (Septiembre, 2023): 313 - 319

Influence of remediation by electrokinetic on the chemical and geotechnical properties of clayey soil contaminated by copper sulfate

Mahdi O. Karkush[1]*, Shahad D. Ali[1], Junied A. Bakr[2]
[1] Department of Civil Engineering, University of Baghdad, Baghdad, Iraq.
[2] Department of Civil Engineering, University of Anbar, Ramadi, Iraq.
* Corresponding author: mahdi_karkush@coeng.uobaghdad.edu.iq
ORCID number: 0000-0003-1304-0303

ABSTRACT

The enhanced electrokinetic (EK) technique is an innovative approach and increasingly used in remediation of the fine-grained texture soils contaminated with different types of contaminant. In this study, the EK is enhanced by adding an intermediate compartment and using purging solutions at the electrode's compartments. The natural clayey soil samples were obtained from Al-Ahadab oil field and artificially contaminated with two ratios of copper sulfate (66666.67 and 26666.67 mg/kg). The feasibility of using EK technique was evaluated by the efficiency of extracting copper from soil and the magnitude of recovery in the geotechnical properties of soil. The duration of remediation was continued for about 240-250 hours depending either on the continuity of electroosmosis flow or reach a constant rate of electrical current. The removal efficiency of copper from contaminated soil samples was ranged from 98.4% to 99.6%. The EK remediation technique proved a marginal impact on the specific gravity and Atterberg's limits, but it has a significant effect on the shear strength parameters and compressibility of soil. Furthermore, the EK technique can be considered an efficient method for removing the low and high concentrations of copper sulfate from clayey soil of low permeability.

Keywords: Remediation; copper sulfate; electrokinetic; heavy metals; geotechnical properties; clayey soil.

Influencia de la remediación electrocinética en las propiedades químicas y geotécnicas de suelos arcillosos contaminados con sulfato de cobre

RESUMEN

La técnica de Electrocinética Mejorada (EK) es una acercamiento innovador que ha incrementado su uso en la remediación de suelos de textura de grano fino contaminados con diferentes fuentes. En este estudio, la técnica EK se mejoró al adicionar una sección intermedia y usar soluciones de purificación en las secciones de electrodos. Las muestras naturales de suelos arcillosos se obtuvieron del campo petrolífero Al-Ahadab y se contaminaron artificialmente con dos adiciones de sulfato de cobre (66666.67 y 26666.67 mg/kg). La viabilidad de usar la técnica de Electrocinética Mejorada se evaluó por la eficiencia al extraer el cobre de la muestra y la magnitud de la recuperación de las propiedades geotécnicas del suelo. La duración de la remediacion fue continuada entre 240 y 250 horas dependiendo en la continuidad del flujo de electroósmosis o en alcanzar una corriente eléctrica estable. La eficiencia en la remoción de cobre en muestras de suelo contaminado osciló entre 98.4 % y 99.6 %. La técnica de remediación por electrocinética mejorada presentó un impacto marginal en la gravedad específica y en los límites de Atterberg pero tuvo un efecto significativo en los parámetros de resistencia a la cizalladura y compresibilidad del suelo. Además, la técnica EK puede considerarse un método eficiente para la remoción de pequeñas y altas concentraciones de sulfato de cobre en suelos arciollos de baja permeabilidad.

Palabras clave: Remediación de suelos; sulfato de cobre; electrocinética; metales pesados; propiedades geotécnicas; suelos arcillosos.

Manuscript received: 14/09/2020
Accepted for publication: 13/09/2023

How to cite item:
Karkush, M. O., Ali, S. D., & Bakr, J. A. (2023). Influence of Remediation by Electrokinetic on the Chemical and Geotechnical Properties of Clayey Soil Contaminated by Copper Sulfate. *Earth Sciences Research Journal,* 27(3), 313-319. https://doi.org/10.15446/esrj.v27n3.90532

ISSN 1794-6190 e-ISSN 2339-3459
https://doi.org/10.15446/esrj.v27n3.90532

List of notations

C1 is the symbol of soil sample contaminated with 66666.67 mg/kg of copper sulfate
C1R is the symbol of soil sample C1 after remediation by EK method
C2 is the symbol of soil sample contaminated with 26666.67 mg/kg of copper sulfate
C2R is the symbol of soil sample C2 after remediation by EK method
CaO is calcium oxide
c_c is the compression index
Cd is the cadmium
C_f is the final concentration
C_i is the initial concentration
Cl^{-1} is chloride content
c_r is the recompression index
Cu is the copper in soil
c_u is the undrained shear strength
c_v is the consolidation coefficient
e_o is the initial void ratio
E_R is the removal efficiency
GL is the ground level
Gs is the specific gravity
k is the coefficient of permeability
LL is the liquid limit
m_v is the coefficient of volume compressibility
OMC is organic matter content
Pc is the preconsolidation pressure
Pb is the lead
pH is the power of hydrogen
PL is the plastic limit
SiO_2 is silicon dioxide
SO_3 is sulfur trioxide
TSS is the total soluble salts
USEPA is the United States Environment Protection Agency
ε is the axial strain

1. Introduction

The urban development and industrial expansion in the world have produced a remarkable increase in the sources and quantity of contaminants, one of the common problems is soil contamination with heavy metals (HMs). The excessive use of pesticides and fertilizers, leakage from storage tanks and pipes, municipal wastes disposal without treatment, and industrial wastes are the main sources of contaminants in soil (Wuana and Okieimen, 2011; Shehzad *et al.*, 2015).

The demand for soil remediation has recently increased to control contamination and exploit the contaminated sites especially in the countries that have a limited area of land. However, many methods can be used in the remediation of contaminated sites, where the selection of suitable methods for remediation depends on the type of soil, type of contaminants, the concentration of contaminants, and the change and continuity in the source of contamination. The EK method is one of the most reliable methods that can be used to remove the HMs from fine-grained textured soils. These soils have low permeability, complex structure, and heterogeneous state (e.g., clay lenses inside the sand structure). Sometimes, the soils may be contaminated by several contaminants (e.g., organic compounds integrated with heavy metals), and therefore combined techniques can be used for remediation of the contaminated soils (Reddy, 2010).

Faisal and Hussein (2013) carried out numerical modelling for the 1-D mass transport equation to simulate the transport copper in the soil during the remediation process by the EK method. The influence of several factors such as pH, adsorption, aqueous phase reaction, and precipitation on the transport phenomena was investigated by the proposed numerical model. Further, the constant electrical current was assumed with time and the effects of temperature and dissolution of soil constituents during the remediation process were ignored during the simulation of the problem. The pH profile and concentration of copper in the sandy soil predicted by the numerical model were in good agreement with those measured experimentally (Faisal and Hussein, 2013). The relationship between the geochemical properties of soil and the ability of soil for retention of heavy metals (Pb and Cd) depend on the type of soil and heavy metal, where the retention ratio ranges from 10 to 100% (Defo *et al.*, 2016). Also, this study demonstrated that the organic matter content has a major influence on the retention of Pb and Cd in the Ntem watershed soil while the clay content, pH, and cation exchange capacity have a slight effect.

However, Chinade et al. (2017) studied the impacts of the chemical solution that contains different types and concentrations of heavy metals on the shear strength of the soil. The unconfined compression strength tests were conducted on soil samples exposed to chemical solutions infiltration for several periods of 7, 21, 42, 84, and 120 days. The results of tests proved that the shear strength was reduced when the period of permeating by the infiltration of municipal solid wastes was increased.

Chen et al. (2019) investigated the impacts of the electrokinetics-persulfate process on the remediation of soil artificially contaminated with decabromodiphenyl ether (BDE-209) and copper. The results show that there was significant removal of BDE-209 and Cu from the soil. MCD assisted process gave the highest BDE-209 removal (88.6%) and the third largest Cu removal (54.3%) from the soil. Comparatively, the highest Cu removal (92.5%) and the second largest BDE-209 removal (85.6%) were achieved by the joint application of MCD and citric acid in anolyte during the EK-persulfate treatment. Shen et al. (2020) investigated the effect of electric potentials on the efficiency of EK remediation on the removal of Cu and Zn from soil. The results of study showed increasing the removal efficiency of Cu and Zn with increasing the electric potential of the cathode from 0 to 10 V. Also, the ion migration to maintain electrical neutrality played an additional role in the variations in Cu and Zn removal-efficiencies and energy consumption. Mostly, increasing the electric potentials causes raising the temperature of soil which causes evaporation of soil moist and may causes reverse osmosis.

Sharma and Kumar (2020) reviewed using utilization of industrial waste-based geopolymers in the stabilization of soft and weak soil. In addition to the improvement of geotechnical properties of soil, the study focused on the cost and the amount of CO_2 gas emission and it is responsibility of global warming. Effects of different parameters of geopolymers such ratios of mixing (%), molarity, temperature, curing time, alkaline activator ratio, and water/cement ratio on the geotechnical properties of soil have been discussed. Ghobadi et al. (2021) used electrokinetic remediation technology integrated with compost as recyclable reactive filter media for removal of copper from kaolinite soil The compost placed near the cathode served as an adsorbent to bind copper ions while buffering the advancement of the alkaline front in soil. The total copper removal rate increased from 1.03% in EK to 45.65% in EK with 100% of compost under an electric gradient of 10 V.

In the present study, the natural fine-grained textured soil sample was contaminated with two ratios of copper sulfate (66666.67 and 26666.67 mg/kg) for 30 days and treated by enhanced EK method for 240-250 hours. The EK method is enhanced by using several purging solutions and mid-compartment of activated carbon to increase the efficiency of this method for removing copper sulfate from the soil. The geotechnical and chemical characteristics of soil are measured before and after remediation to evaluate the efficiency of the proposed EK method in the remediation of clayey soil samples contaminated with copper sulfate. The efficiency of the remediation technique can be evaluated either by the removal efficiency of contaminant from soil or by the magnitude of recovery of the key geotechnical properties such as shear strength and compressibility of soil.

2. Effects of Heavy Metals on Geotechnical Properties of Soil

Heavy metals have been produced from different sources and they have a severe influence on the geotechnical properties of soil. Table 1 shows the maximum concentration of heavy metals in soil (Saleem et al., 2011). The heavy metals adhere to the particles of soil and they are immobile. This process is called sorption and describes the heavy metal distribution between the solid and the soil solution. Sorption can be divided into adsorption and absorption, where adsorption is the critical mechanism of sorption. Adsorption can be defined as binding the contaminants on the surface of the soil while absorption can be described as the binding of these contaminants in solid components of the soil. The primary mineral components of soil such as clay minerals, organic matter, silica, aluminium, iron, manganese oxides, carbonates, and phosphates sorb heavy metals (Nystrøm, 2001).

Table 1. Maximum concentration levels of HMs in soil (Saleem et al., 2011).

Heavy metal	Maximum level in soil, mg/kg	
	USEPA	Dutch standards
Mercury (Hg)	0.5	0.3
Cadmium (Cd)	0.6	0.8
Selenium (Se)	1.7	0.7
Arsenic (As)	14	29
Cobalt (Co)	20	9
Nickel (Ni)	32	35
Lead (Pb)	60	85
Copper (Cu)	100	36
Chromium (Cr)	120	100
Zinc (Zn)	220	140

Up to date, very limited studies have been studied the effect of heavy metals on the geotechnical properties of soil and these studies addressed that the presence of heavy metals in the soil mass causes a reduction in the shear strength parameters of soil, cohesion (c) and angle of internal friction (φ). However, it was also observed that the presence of heavy metals in the soil raises compressibility, increases the average dry density, and reduces the optimal soil moisture content and permeability. Studies on the impact of heavy metals on soil geotechnical properties are however quite limited (Karkush et al., 2013).

3. Electrokinetic Remediation Technique

The EK is one of the most well-known recent technique developed to remove the heavy metals and/or organic compounds from the contaminated soils which have low permeability (Karim, 2014). This remediation method can extract contamination (radionuclides, certain organic compounds, and heavy metals) from the soil or groundwater by applying an electrical current between two electrodes. During the application of DC electrical current, three phenomena can occur electroosmosis, electromigration, and electrophoresis. Several previous studies have shown that the use of water as an electrolyte is an ineffective way to give a high removal efficiency of contaminant, especially when the soil is contaminated with two or more contaminants. Therefore, several techniques can be combined with the EK method to improve the removal efficiency of contaminants from the soil as listed below:

a. Increasing the period required for treatment, but it is limited by the flow of electrical current and osmotic flow.
b. Increasing the electric gradient, but is limited by the temperature of the soil sample.
c. Using the improvement of chemical solutions (solvents or surfactants).
d. Using washing by chemical solutions.

The use of purging solutions in the electrodes compartment is the most promising strategy for obtaining high removal efficiency of contaminant from soil or groundwater (Reddy, 2013). According to the type of contaminant and soil, it can be identified the type and concentration of purging solution. Also, soil washing is one of the remediation techniques that can integrated with the EK method (Dermont *et al.*, 2008). Soil washing is ordinarily utilized for isolating the contaminants from soil particles and the most contaminated fraction of the soil will be disposed outside of the site, where several extracting fluids such as acids/bases, salts, chelating agents, surfactants, or redox agents can be used to move the metals from the soils into the hydrous solution.

4. Experimental Work

The experimental work consists of two main stages: the fieldwork stage and laboratory work stage. The fieldwork involves soil sampling and measuring the field total density and moisture content. However, the laboratory work includes investigating the influence of EK method remediation on the geotechnical and chemical properties of soil samples contaminated with copper sulfate by conducting a wide range of traditional laboratory tests (Karkush and Ali, 2019a).

Soil Sampling and field tests

The natural soil samples are obtained from Al-Ahdab oil field in the east of Iraq by digging a trial pit to a depth of 3 m under the ground level (GL) and the groundwater table encountered at depth of 2.65 m from the GL. The field density of soil was 1984 kg/m^3 measured according to ASTM (D2937) and the water content was 28.6% measured according to ASTM (D2216) (Karkush and Ali, 2019a).

Contamination of soil samples

Two soil samples are contaminated artificially in the laboratory with two ratios of copper sulfate (66666.67 and 26666.67 mg/kg) to investigate the influence of contaminants on the geotechnical and chemical properties of clayey soil samples. The soil samples are soaked by contaminant solutions for thirty days in two separate plastic containers. The duration of saturation, 30 days, is assumed enough to complete the chemical reactions between the contaminant and mineral composition of the soil (Karkush *et al.*, 2013)). Further, this duration should be enough for contaminant to reach the farthest points in the soil and ensure homogenous distribution for the contaminant in the soil samples. It can be confirmed this state visually by using transparent plastic containers. The contaminant solution consists of copper sulfate (100 and 400) g and 10 L of distilled water. The quantity of water used in this process must be enough to cover the soil sample and the saturation of soil samples (Zhou *et al.*, 2004; Karkush *et al.*, 2013). The designation of soil specimens, the concentrations of copper sulfate ($CuSO_4.5H_2O$), and copper (Cu) used in the current study are given in Table 2.

Table 2. Definition of tested soil samples.

Soil sample	Definition	Concentration of copper sulfate	Concentration of copper
C1	Remolded soil sample contaminated with 100 g of copper sulfate ($CuSO_4.5H_2O$)	66666.67 mg/kg	1696.732 mg/kg
C1R	Decontaminated soil sample C1 with enhanced EK method	-	-
C2	Remolded soil sample contaminated with 400 g of copper sulfate ($CuSO_4.5H_2O$)	26666.67 mg/kg	6786.933 mg/kg
C2R	Decontaminated soil sample C2 with enhanced EK method	-	-

Remediation of contaminated soil samples

The EK setup utilized for remediation of contaminated soil samples consists of two main compartments (cathode and anode) in addition to the suggested mid compartment of activated carbon. The EK cell has a length of 50 cm, and a height of 10 cm of high with 10 cm of width, and it was supplied with a power supply and multimeter as shown in Figure 1. The dimensions of carbon electrodes used in this study are 10 cm of width, 10.5 cm of height and 2 cm of thickness and the used voltage gradient is 1.3 VDC/cm. The EK method setup is enhanced in two ways: using a purging solution in the three compartments instead of distilled water and using an activated carbon barrier. The purging solutions used in this study are 0.001 M of nitric acid (HNO_3) at the anode, mid, and cathode compartments at the beginning of the test. When the pH value at the anode compartment reaches to a value about 2, the purging solution is replaced by 0.1 M of sodium hydroxide (NaOH) to keep the value of pH higher than 2 to prevent the reverse electroosmotic flow from occurring (Karkush and Ali, 2019a). Also, the anolyte was circulated with controlled constant flow rate during the test as shown in Figure 1. The remediation period is continued for

240-250 hours and it is stopped when the electrical current becomes constant or there is no osmotic flow.

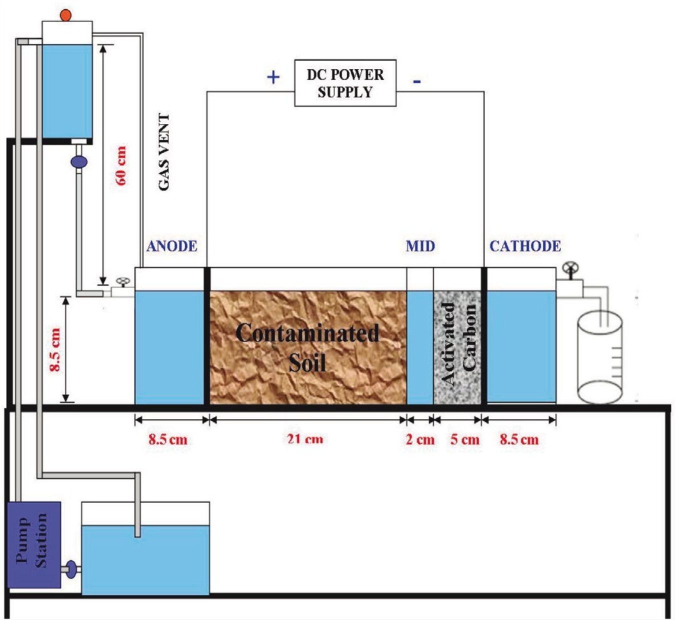

Figure 1. The EK setup used in the remediation of soil samples.

Chemical and Geotechnical Properties of soil

A specific laboratory-testing program is carried out on contaminated and decontaminated soil samples in the laboratory of soil mechanics at the University of Baghdad. The chemical and geotechnical properties of soil samples are measured according to the ASTM standards. Understanding the effects of contamination by copper sulfate and remediation by EK method requires detailed testing program to measure the mineral composition of soil samples and the variation in the physical and mechanical properties of these soil samples. The copper sulfate has a significant influence on the chemical and geotechnical properties of clayey soil. Therefore, the use of such soils in the construction or as the foundation for the structures makes researchers think seriously in the remediation of such soils before they decide to use them (Karkush and Ali, 2019a).

5. Results and Discussion

The removal efficiency of copper from the soil samples after remediation by EK method can be calculated by:

$$E_{R,\,Cu} = (C_i - C_f)/\,C_i \times 100 \qquad (1)$$

where

$E_{R,\,Cu}$: is the is the removal efficiency of copper from the soil.

C_i: is the initial concentration of copper in the soil (mg/kg).

C_f: is the final concentration of copper in the soil (mg/kg).

The initial and final concentrations of copper in the soil samples can be computed by:

$$Cu\,(\%) = \frac{Atomic\ mass\ of\ cu \times used\ quantity}{Atomic\ mass\ of\ CuSo_4{\bullet}5h_2o} * 100 \qquad (2)$$

According to Equation 2, the initial and final concentrations of copper in the tested soil samples and the removal efficiency of copper from contaminated soil samples calculated by using Equation 1 are given in Table 3 (Karkush and Ali, 2019a). The use of the enhanced EK method in the remediation of clayey soil contaminated with copper sulfate is very efficient regardless of the initial concentration of copper sulfate in the soil samples.

Table 3. Removal efficiency of copper from tested soil samples.

Initial concentration of copper mg/kg	Final concentration of copper mg/kg	Removal efficiency %
1696.732 Soil sample C1	27.56 Soil sample C1R	98.4
6786.933 Soil sample C2	28.46 Soil sample C2R	99.6

Impacts of copper on the chemical properties of soil

The chemical composition of clayey soils plays an important role in determining the geotechnical properties of soils, especially when the soil samples are contaminated. The chemical tests conducted on the soil samples before and after remediation to measure the contents of SO_3, Cl^{-1}, SiO_2, CaO, OMC, gypsum, pH, and TSS to evaluate the impacts of remediation process on the chemical composition of the soil samples. These tests conducted according to the ASTM specifications. The results of the chemical tests are presented in Table 4. It can be noted from Table 4 that the remediation by EK method causes a reduction in the contents of SO_3, Cl^{-1}, SiO_2, OMC, gypsum, and TSS because of adsorption of these compounds by the surrounded soil particles. However, the EK method causes increasing the contents of CaO and pH value of soil. A strong alkaline used as a purging solution in the EK method causes a slight rise in the pH value of soil. Based on this, it can be generally said that the EK method has slight impacts on the contents of SO_3, SiO_2, CaO, and pH value while it has significant influences on the contents of Cl^{-1}, OMC, gypsum, and TSS.

Table 4. Results of chemical tests conducted on soil samples.

Soil sample	SO_3 %	Cl^{-1} %	Quartz %	CaO %	OMC %	Gypsum %	pH value	TSS %
C1	0.620	0.836	32.58	17.93	0.610	0.043	7.5	3.53
C1R	0.572	0.416	32.48	18.28	0.551	0.031	7.6	2.59
C2	0.293	1.187	31.64	18.11	0.656	3.56	7.3	6.92
C2R	0.291	0.819	33.41	18.12	0.637	3.23	7.4	2.33

Impacts of Copper on Physical Properties of Soil

The results of particle-size distribution, Atterberg limits, specific gravity, and hydraulic conductivity of tested soil samples are presented in Table 5 and the particle-size distribution curves are shown in Figure 2. The physical properties of soil samples are measured according to the ASTM standards. It can be observed that the contamination by copper sulfate causes increasing of the sizes of the soil particles and increasing the concentration of copper sulfate in the soil leads to a reduction in the percentage of fine particles in the soil samples. Accordingly, the stability of aggregates in the soil is noted to be increased because the copper metal (Cu^{+2}) can adsorb on the surfaces of clay particles and create a cation bridge between the clay particles. However, after the remediation process, the percentage of fine particles is observed to be increased while the percentage of sand and silt tends to be decreased. It can be confirmed based on the previous observations that although the contaminants are removed from soil by using the EK method, the percentage of sand and silt is still less than that of natural soil samples because the salts of copper sulfate are not completely extracted from the soil after the remediation process.

The specific gravity of soil samples is increased with increasing the content of copper sulfate in the soil. This result may be attributed to the precipitation of copper sulfate in the pores of soil and the specific gravity of copper sulfate ishigher than that of natural soil (Karkush *et al.*, 2013). After the remediation process, it can be observed that there was insignificant decrease in the values of specific gravity. A possible explanation for these results may be the migration of dissolved salts and colloids in leaching water during the EK method. Besides, the increase of the content of copper sulfate in the soil samples causes a reduction in liquid and plastic limits (Karkush and Ali, 2019a), but the remediation by the EK technique leads to increasing the liquid limit by 8 and 8.7% in soil samples CR1 and CR2, respectively.

The liquid limit increased because the content of fine particles in the soil samples after remediation is increased and the removal of copper sulfate from the soil is increased the reactions between charged clay particles with water. The PL of soil sample CR1 does not change after remediation, but in soil sample (CR2) is increased by 8.7%. The hydraulic conductivity of soil samples tested by falling head tests (FHT) is reduced by increasing the content of copper sulfate in the soil specimen, where the hydraulic conductivity of soil sample C2 is less than of soil sample C1 by 33%.

Table 5. Physical properties of tested soil samples.

Soil Samples	Sand %	Silt %	Clay %	Gs	LL %	PL %	k×10^{-8} cm/sec
C1	0.104	34.896	65.0	2.77	50	27	1.63
C1R	0.103	28.891	71.0	2.76	54	27	-
C2	0.285	47.432	52.0	2.82	46	23	1.06
C2R	0.188	36.812	63.0	2.79	50	25	-

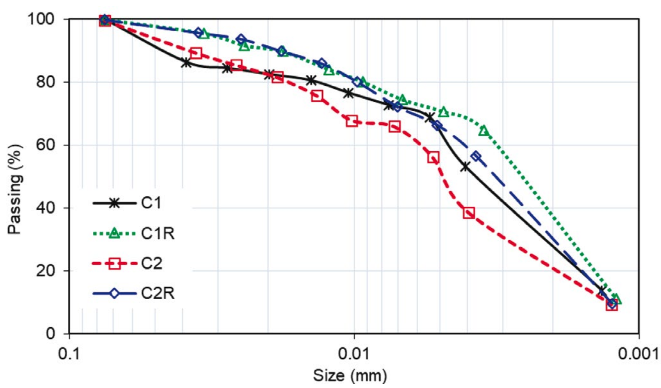

Figure 2. Particle size distribution curves of tested soil samples.

Impacts of Copper on Mechanical Properties of Soil

The stability of structures foundations depend on the compressibility and shear strength of soils beneath them, and therefore the structures can be damaged or collapsed if the soil fails in shear strength and/or the compressibility exceeds the allowable limits. Well understanding of the shear strength and compressibility of the soil is necessary to design the foundations and earth structures. The copper sulfate contamination causes a significant decrease in the shear strength parameters and the compressibility parameters of soil (Karkush and Ali, 2019b). The remediation by the EK method is used to regain the strength of soil lost by contamination. The consolidation parameters are obtained in the current study by conducting a 1-D consolidation test while the shear strength parameters are obtained by performing the unconfined compressive strength test (UCS) and unconsolidated undrained triaxial test (UUT).

The results obtained from 1-D consolidation tests are the initial void ratio (e_o), compression index (c_c), swelling index (c_r), preconsolidation pressure (Pc), coefficient of volume compressibility (m_v), and coefficient of consolidation (c_v) and they are presented in Table 6. Further, the variation of void ratio with pressure obtained from 1-D consolidation test is shown in Figure 3. The coefficient of consolidation (c_v) is increased after remediation by the EK method. A possible explanation for these results may be the increase of the hydraulic conductivity of the contaminated soil samples. However, the compression and swelling indices are noted to be increased for the tested soil samples, and there are several reasons caused this action: (1) the presence of copper as a lubricant agent in the voids of soil could cause the sliding of soil particles; (2) the nature of the fluid and the charge of the soil particles could influence the adsorbed cations; and (3) perhaps, this increase caused by dissolving of salts (Grim, 1968; Karkush and Altaher, 2017).

It can be also noted that the contamination causes increasing the coefficient of volume change and this could be because of the re-arrangement of the recently bonded soil particles into the macro voids generated from contamination of soil samples with copper sulfate. In the soil matrix, this reaction causes the generation of a large space between the particles of soil (Ota, 2013). After remediation, it can be noted that the initial void ratio is decreased, but the compression index, swelling index, the coefficient of volume change, and the coefficient of consolidation are increased relative to the corresponding values of contaminated soil specimens.

Table 6. Compressibility and shear strength parameters of soil samples.

Soil sample	1-D Consolidation test						UCS		UUT
	e_o	c_c	c_r	P_C kPa	m_v m²/kN	c_v cm²/sec	ε %	c_u kPa	c_u kPa
C1	0.881	0.123	0.033	45	0.00027	0.00018	9.276	65.52	94.145
C1R	0.829	0.199	0.046	110	0.00044	0.00032	12.223	68.09	105.99
C2	0.893	0.125	0.034	33	0.00046	0.0001	17.039	18.82	23.28
C2R	0.866	0.205	0.045	33	0.00089	0.00042	16.710	26.65	74.35

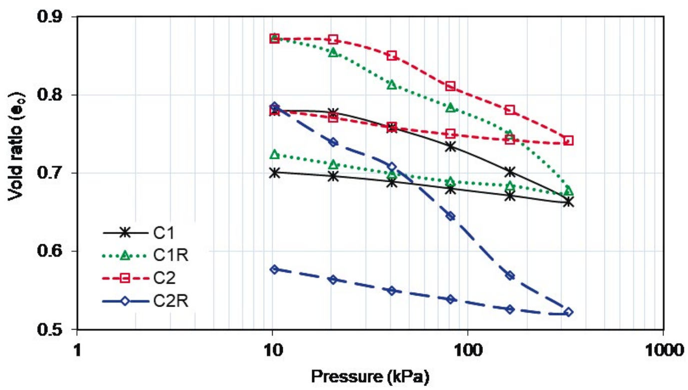

Figure 3. Void ratio versus pressure of tested soil samples by 1-D consolidation tests.

The shear strength of soil samples has been measured before and after remediation by EK method using (UCS) and (UUT) tests. The results recorded from UCS are given in Table 6 and the stress-strain relation is shown in Figure 4. The contamination of soil by heavy metals (HMs) has a negative impact on the undrained shear strength of the soil. The contaminated soil samples (C1 and C2) are classified according to the undrained shear strength as firm and very soft soil respectively (Craig, 2004). The lower value of shear strength parameters of contaminated soil samples is obtained because of the presence of the dissolution of salts that connect the particles of soil altogether and consequently, the contact area between the soil particles will be reduced, where the percentage of fines is decreased by contamination and this ratio is increased after remediation (Karkush and Altaher, 2017). However, it can be observed that the undrained shear strength of soil samples after remediation is increased by 3.92 and 29.55% for the soil samples C1R and C2R respectively.

The undrained triaxial tests (UUT) are conducted on soil samples before and after remediation under different cell pressure (100, 200, and 300) kPa. In UUT test, the angle of internal friction (φ) is equal to zero if the soil is completely cohesive and fully saturated, so if the degree of saturation is not equal to 100%, the failure envelope of Mohr-Coulomb circles is usually a curve and that the angle of internal friction (φ) is not equal to zero (Ota, 2013). The results obtained from UUT test are given in Table 6 and the variation of deviatoric stress with the axial strain is shown in Figure 5. The results obtained from UUT are demonstrated that the copper has a high impact on the undrained shear strength of the soil and the EK remediation method remarkably influences the recovery of the undrained shear strength of contaminated soil samples. It is observed that the undrained shear strength is recovered by 13 and 220% for the soil samples C1R and C2R respectively. Generally, both UCS and UUT showed the same trend of stress-strain relation, but the results of the UUT test are still considered more reliable than UCS test due to neglecting the effect of confining pressure in UCS.

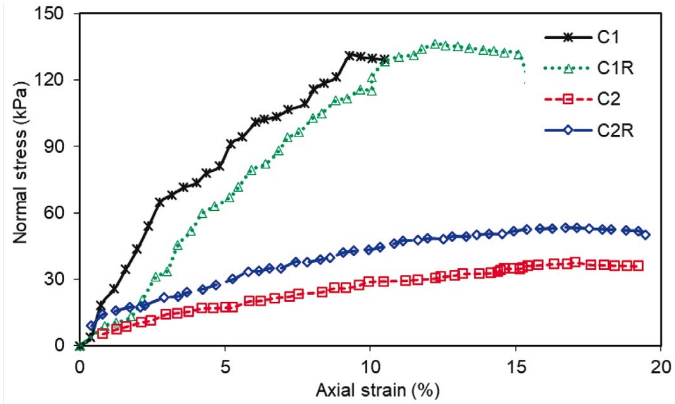

Figure 4. Stress-strain relationships for soil samples obtained from unconfined compressive strength tests.

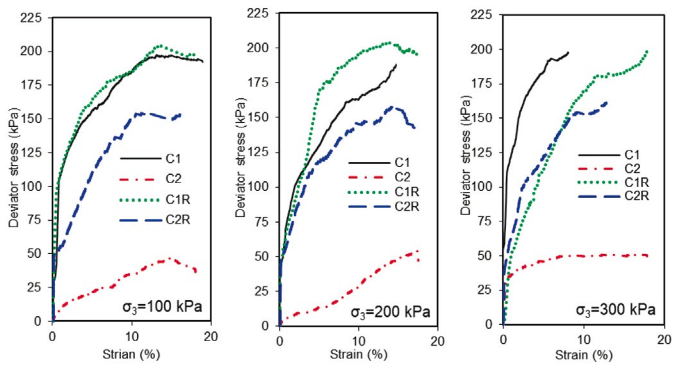

Figure 5. Deviator stress versus axial strain for soil samples obtained from unconsolidated undrained triaxial tests.

6. Conclusions

The present study investigates the impacts of remediation of clayey soil samples contaminated with two percentages of copper sulfate using enhanced EK technique on the chemical and geotechnical properties of soil samples. The main conclusions from this work are:

- The copper sulfate has slight effects on the particle-size distribution curve, but the remediation of contaminated soil specimens has contributed to an increase of the percentage of fines particles having a size less than 0.005 mm and a slight impacts on the Atterberg's limits and the specific gravity of clayey soil samples.
- The compressibility parameters such compression index (c_c) and the coefficient of consolidation (c_v) are adversely increased after remediation.
- The undrained shear strength of the soil is recovered after remediation by enhanced EK technique. The magnitude of recovery increased significantly with increasing the initial concentration of copper in the soil samples.
- The results of tests reflected a remarkable efficiency for the enhanced EK method in removal copper from low permeability clayey soil.

Acknowledgments

The authors would like to acknowledge the department of civil engineering at the University of Baghdad for their help in conducting the traditional tests of this work.

References

Chen, F., Li, X., Ma, J., Qu, J., Yang, Y., & Zhang, S. (2019). Remediation of soil co-contaminated with decabromodiphenyl ether (BDE-209) and copper by enhanced electrokinetics-persulfate process. *Journal of hazardous materials*, 369, 448-455. https://doi.org/10.1016/j.jhazmat.2019.02.043

Chinade, A. U., Umar, S. Y., & Osinubi, K. J. (2017). Effect of municipal solid waste leachate on the strength of compacted tropical soil for landfill liner. *International Research Journal of Engineering and Technology*, 4(6), 3248-3253.

Craig, R. F. (2004). *Craig's Soil Mechanics*. 7th ed., Spon Press: imprint of Taylor and Francis Group, London and New York.

Defo, C., Yerima, B. P. K., & Bemmo, N. (2016). Investigating soils retention ratios and modelling geochemical factors affecting heavy metals retention in soils in a tropical urban watershed. *Environment, Development and Sustainability*, 19(5), 1649-1671. https://doi.org/10.1007/s10668-016-9819-2

Dermont, G., Bergeron, M., Mercier, G., & Richer-Laflèche, M. (2008). Soil washing for metal removal: A review of physical/chemical technologies and field applications. *Journal of Hazardous Materials,* 152(1), 1-31. https://doi.org/10.1016/j.jhazmat.2007.10.043

Faisal, A. A., & Hussien, A. A. (2013). Setuping and simulation of Copper removal from the contaminated soil by a combination of adsorption and electro-kinetic. *Journal of Engineering*, 19(6), 695-716.

Ghobadi, R., Altaee, A., Zhou, J. L., McLean, P., Ganbat, N., & Li, D. (2021). Enhanced copper removal from contaminated kaolinite soil by electrokinetic process using compost reactive filter media. Journal of Hazardous Materials, 402, 123891. https://doi.org/10.1016/j.jhazmat.2020.123891

Grim, R. E. (1968). *Clay Mineralogy.* 2nd ed., McGraw-hill Book Company.

Karim, M. A. (2014). Electrokinetics and soil decontamination: concepts and overview. *Journal of Electrochemical Science and Engineering*, 4(4), 297-313. https://doi.org/10.5599/jese.2014.0054

Karkush, M. O., & Ali, S. D. (2019a). Remediation of clayey soil contaminated with copper sulfate using washing-enhanced electrokinetics technique. *Russian Journal of Electrochemistry*, 55(12), 1381-1390. https://doi.org/10.1134/S1023193519130020

Karkush, M. O., & Ali, S. D. (2019b). Effects of copper sulfate contamination on the geotechnical behavior of clayey soils. *Journal of GeoEngineering*, 14(1), 47-52. DOI: 10.6310/jog.201903_14(1).6

Karkush, M. O., & Altaher, T. A. (2017). Remediation of contaminated soil of Thi-Qar oil refinery plant. *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering* (Vol. 1).

Karkush, M. O., Zaboon, A. T., & Hussien, H. M. (2013). *Studying the effects of contamination on the geotechnical properties of clayey soil.* Coupled Phenomena in Environmental Geotechnics, Taylor & Francis Group, London: 599-607.

Nystrøm, G. M. (2001). *Investigations of soil solution during enhanced electrodialytic soil remediation*. Byg Rapport, No. R-009. http://www.byg.dtu.dk/publications/rapporter/byg-r009.pdf.

Ota, J. O. (2013). *The effect of light crude oil contamination on the geotechnical properties of kaolinite clay soil.* Ph.D. thesis, College of Engineering, Anglia Ruskin University.

Reddy, K. R. (2010). Technical challenges to in-situ remediation of polluted sites. *Geotechnical and Geological Engineering,* 28(3), 211-221. https://doi.org/10.1007/s10706-008-9235-y

Reddy, K. R. (2013). Electrokinetic Remediation of soils at complex contaminated sites: technology status, challenges, and opportunities. *Coupled Phenomena in Environmental Geotechnics,* 131-147.

Saleem, M., Chakrabarti, M., Irfan, M., Hajimolana, S., Hussain, M., Diya'uddeen, B., & Daud, W. (2011). Electrokinetic Remediation of Nickel From Low Permeability Soil. *International Journal of Electrochemical Science,* 6(9), 4264-4275. https://doi.org/10.1016/S1452-3981(23)18326-X

Sharma, K., Kumar, A. (2021). *Geotechnical Behaviour of Copper Slag Mixed with Different Proportions of Soil, Lime, Fly Ash and Cement—A Review*. In: Reddy, K.R., Agnihotri, A. K., Yukselen-Aksoy, Y., Dubey, B. K., Bansal, A. (eds) Sustainable Environment and Infrastructure. Lecture Notes in Civil Engineering, vol 90. Springer, Cham. https://doi.org/10.1007/978-3-030-51354-2_10

Shen, X., Li, C., Li, M., Zhou, K., & Li, Y. (2021). Effect of electric potentials on the removal of Cu and Zn in soil by electrokinetic remediation. *Separation Science and Technology,* 56(14), 2439-2448. https://doi.org/10.1080/01496395.2020.1825967

Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. *International Scholarly Research Notices*, 402647. https://doi.org/10.5402/2011/402647

Zhou, D., Deng, C., & Cang, L. (2004). Electrokinetic remediation of a Cu contaminated red soil by conditioning catholyte pH with different enhancing chemical reagents. *Chemosphere,* 56(3), 265-273. https://doi.org/10.1016/j.chemosphere.2004.02.033